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PAVEMENT DEFLECTION MEASUREMENT BY AN INDIRECT RESPONSE METHOD

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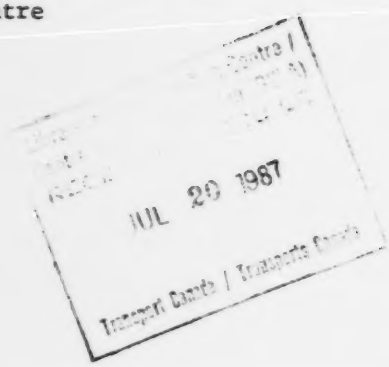

by

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September, 1986

The contents of this report reflect the views of Highway Products International Inc. and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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17. Abstract

The objective of this study was to develop and evaluate a method of pavement deflection measurement suitable for operation at up to 60 km/h. A statically operated prototype was fabricated and tested, and a computer model of its operation was developed. Test results were compared to results from the SIE Dynaflect deflection device. A good correlation on a variety of roads and construction types was found. The computer model was useful in explaining the few shortcomings of the response method and in pinpointing ways to eliminate these shortcomings. Preliminary designs which use the response method under dynamic operation were outlined. The response method was successful in deflection measurement and suitable for implementation in dynamic operation.

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17. Résumé

Ce rapport de recherche concerne l'étude et l'évaluation d'une méthode pour mesurer la déflexion d'une chaussée, utilisant un mobile qui avance à 60 km/h. Un prototype d'appareil de mesure sous charge statique ainsi qu'un programme informatique modélisant son fonctionnement ont été réalisés et essayés. Les résultats obtenus par cet appareil ont été comparés à ceux d'un déflectomètre Dynaflect de la SIE. Une bonne corrélation a été obtenue à l'égard de chaussées de type et de construction variables. Grâce au programme informatique les quelques faiblesses de cette technique ont pu être expliquées et les moyens de les corriger dégagés. Le principe d'un appareil de mesure sous charge dynamique a été décrit. Le rapport conclut que la méthode donne des résultats satisfaisants et qu'elle peut être adaptée à la mesure sous charge dynamique.

18. Mots-clés	19. Diffusion
Chaussées, rues, routes, essais mécaniques, déflexion, poutre Benkelman	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

The structural strength of a roadway is a key factor in characterizing a pavement and in determining rehabilitation strategies for a roadway or road surface. Currently available equipment for measuring structural strength requires stopped or near-stopped operation for obtaining the measurement. This mode of operation is intrinsically dangerous on high-speed roadways, and inhibits the thorough sampling of structural strength in a large roadway network.

This study investigated a method of measuring roadway structure that is particularly suited for implementation at speeds of up to 60 km/h. The method involved instrumenting an impact probe and characterizing its response during an impact blow on a pavement surface. Most methods of pavement strength (deflection) determination require the instrumentation of the road surface itself.

The testing outlined in this report was conducted with a stationary prototype. The impact response was characterized by the peak deceleration, peak rebound velocity, and maximum pavement penetration of the impact probe. These results were compared to results obtained with an SIE Dynaflect. Both peak acceleration and rebound velocity of the impact probe correlated with Dynaflect measures representing total structure strength.

The study also involved developing a model and a computer simulation program of the probe/pavement impact. This simulation pinpointed several shortcomings of the probe prototype design, and recommendations for redesign to improve the performance of the method and design were outlined.

The extension of this method of measuring pavement structural strength into a moving apparatus was outlined in four concepts for dynamic implementation. The concepts were compared with respect to mechanical complexity, likelihood of achieving an acceptable pavement impact, and complexity of instrumentation. Preliminary specifications of this moving test apparatus were detailed. The equipment should be used for flexible pavements, inflict no significant damage to the pavement surface, operate at up to 60 km/h, function in a wide range of environmental conditions, and with a precision comparable to the Dynaflect.

The study concludes that the impact probe response technique can be used to characterize pavement structural strength, and that the method could be implemented in a moving vehicle. The report recommends further development of the concept towards implementation in a moving vehicle. This development would include expanding the simulation model to include the dynamic motion of the vehicle, selecting one of four concepts for dynamic implementation, fabricating a moving prototype, and conducting an extensive test and evaluation program.

SOMMAIRE

La résistance mécanique d'une chaussée constitue l'un des points fondamentaux à considérer dans l'élaboration de toute stratégie de renforcement et de remise en état. Les appareils de mesure couramment utilisés pour déterminer la résistance mécanique des chaussées reposent sur un principe supposant une avance très lente, sinon l'immobilisation complète du véhicule d'auscultation. Cette sujétion a le double désavantage de mettre en péril les équipes d'auscultation affectées aux voies rapides et d'empêcher, vu la cadence beaucoup trop faible, une auscultation suffisamment serrée des chaussées dans le cas des réseaux routiers très étendus.

Ce rapport rend compte d'une étude sur une méthode de mesure se prêtant particulièrement bien à l'auscultation accélérée des chaussées, le véhicule porteur pouvant circuler à une vitesse maximale de 60 km/heure. Cette méthode fait appel à une sonde dont on enregistre la réponse au contact avec la chaussée à ausculter. L'originalité de la méthode résulte dans le fait que ce n'est plus la chaussée qui est instrumentée, mais bien la sonde d'auscultation.

Les essais rapportés ici ont été réalisés à l'aide d'un prototype de type statique. Les paramètres caractéristiques enregistrés ont été la décélération maximum et la vitesse maximum de rebondissement de la sonde, ainsi que la pénétration maximum de celle-ci dans la chaussée. La comparaison des résultats obtenus avec ceux fournis par un appareil Dynaflect de SIE a révélé une bonne corrélation entre les deux premiers paramètres ci-dessus et les valeurs du Dynaflect exprimant la résistance mécanique globale de la chaussée.

L'énoncé des travaux prévoyait aussi l'élaboration d'un modèle mathématique et d'un programme de simulation par ordinateur pour étudier l'interaction sonde/chaussée lors d'un impact. Cette simulation a mis en évidence plusieurs lacunes de la sonde utilisée et a permis aux chercheurs de dégager les perfectionnements nécessaires en vue d'améliorer l'efficacité de la méthode et de l'appareil lui-même.

L'adaptation de la méthode à la mesure dynamique sur mobile porteur a fait l'objet de quatre propositions. Celles-ci ont été comparées sur les plans de la complexité mécanique, de l'aptitude à réaliser un impact ayant les caractéristiques souhaitées et de la complexité de l'instrumentation de mesure. Par la suite, les spécifications préliminaires de l'appareil d'auscultation mobile envisagé ont été élaborées: utilisation sur chaussée souple, endommagement négligeable de la chaussée, vitesse maximum d'ausculation de 60 km/h, aptitude à fonctionner dans une large gamme de conditions naturelles et précision comparable à celle d'un appareil Dynaflect.

Les chercheurs sont arrivés à la conclusion que la technique d'auscultation envisagée permet effectivement de caractériser la résistance mécanique d'une chaussée et qu'elle pourra être adaptée à l'auscultation par mobile porteur rapide. Le rapport propose de pousser plus avant l'étude de la version mobile de l'appareil et, à cette fin, de rendre le modèle de simulation apte à prendre en compte le mouvement du véhicule porteur, de choisir l'une des quatre propositions visant l'adaptation du concept à l'auscultation dynamique, de réaliser un prototype d'ausculteur mobile et, enfin, d'exécuter un programme exhaustif d'essais et d'évaluation.

TABLE OF CONTENTS

1. INTRODUCTION 1

2. PAVEMENT RESPONSE TESTING 3

3. THEORY OF PAVEMENT RESPONSE 31

4. CONCEPTS OF DYNAMIC IMPLEMENTATION 41

5. EQUIPMENT SPECIFICTAIONS 47

6. RECOMMENDATIONS 53

APPENDIX A. TECHNOLOGY ASSESSMENT 59

LIST OF TABLES

Table 2-1 Response Tests: Data Summary 9
Table 2-2 Response Tests: Data Summary 11
Table 2-3 Response Tests: Data Summary 13
Table 2-4 Response Tests: Data Summary 15

LIST OF FIGURES

Figure 2.1 : Impact Tool 19
Figure 2.2 : Lifting Device 21
Figure 2.3 : Filtered Voltage Plot 23
Figure 2.4 : Filtered Voltage Plot 24
Figure 2.5 : Response vs. Dynaflect: Acceleration 25
Figure 2.6 : Response vs. Dynaflect: Velocity 26
Figure 2.7 : Fault Detection on Waterloo # 49 27
Figure 2.8 : Fault Detection on Brant # 28 29
Figure 6.1 : Prototype Development Schedule 57
Figure A-1 : Response Wheel 64
Figure A-2 : Accelerometer Signal 65

1. INTRODUCTION

The purpose of this study was to develop and evaluate a method of pavement deflection measurement that could be commercially and technically viable under conditions of normal vehicle speed operation. Virtually all commercially available deflection equipment requires stopped or near-stopped vehicle operation. As a result, pavement deflection determination has been a dangerous and time-consuming operation. A worldwide survey of agencies conducting deflection measurements showed that interest was strong for a high speed deflection device, and 80% of respondents indicated willingness to pay over $100,000 for such a device.

The method of pavement deflection measurement developed and evaluated was a response method. A 100 to 300 lb. (45 to 135 kg.) instrumented steel weight was free fall dropped on the pavement. The short contact time with the pavement gave this method good potential for use at vehicle speeds. Interim reports that detail the results of the study as defined by task are:

Task 5.1 Survey

Task 5.2 Technology Assessment

Task 5.3 Response Tests

Task 5.4 Initial Specifications

Task 5.5 Conceptual Realization & Theory

This final report represents a summary of the study.

2. PAVEMENT RESPONSE TESTS

This section outlines the results from impact testing conducted on an array of pavement surfaces.

2.1 BACKGROUND

2.2 TEST SET-UP

2.3 TEST LOCATION

2.4 TEST RESULTS

2.5 ANALYSIS OF TEST RESULTS

2.6 CONCLUSIONS OF RESPONSE TESTS

2.1 BACKGROUND

The "TECHNOLOGY ASSESSMENT" interim report(*) outlined the direction for the development of a High Speed Deflection Measuring Device. It recommended that an indirect or response type measurement be made.

In order to test the feasibility of characterizing a pavement and its sub-structure at 60 km/h with a response measure, a test program was designed to first determine the feasibility and characteristics of static response measurement of pavement. This program tested the applicability of response measurements, and the results provided guidelines for implementing these measurements at high speeds. Detailed description and results of these tests are contained in the "RESPONSE TESTS" report(**).

(*) "A Short Interim Report on the Status of Development of a High Speed Deflection Measuring Device". (Contract # OSD83-00055 Interim Report, September 1984.) See Appendix A.

(**) "A Study of High Speed Measurement by an Indirect Response Method - Response Tests". (contract #OSD83-00055 Working Paper, September 1985.)

2.2 TEST SET-UP

2.2.1 Stimulus

The "TECHNOLOGY ASSESSMENT" report recommended that a free fall impact be used to provide the input stimulus to the pavement. The Static Test Device employed a free fall velocity buildup to impact, allowing a simple design and a brief pavement contact time.

2.2.2 Instrumentation

As recommended in the "TECHNOLOGY ASSESSMENT" report, an accelerometer was chosen to measure pavement response. This provided a much higher raw signal to noise ratio than velocity or displacement transducers. The accelerometer was located on the impact bar. During impact tool contact with the pavement, the accelerometer measured the response characteristics of the pavement.

2.2.3 Impact Tool

A solid steel rod was chosen as the impact bar. The accelerometer was mounted at the top of the bar. At the impact end, provision was made for the attachment of four different impact bits using a retaining pin. The bits provided two different impact weight combinations, and two different impact face combinations. The impact face of the bit was rounded to ensure constant contact area regardless of the levelness of the road. The impact tool is depicted in Figure 2.1.

2.2.4 Lifting Device

A materials hoist with a manual hitch release was used to lift and drop the impact tool from a predetermined height. Figure 2.2 shows the setup.

2.2.5 Data Collection

Due to the anticipated need to massage the raw data signal in order to obtain relevant pavement response parameters, a high-resolution digital data acquisition device was selected. This device, the NICOLET 2090 oscilliscope, stores 4K words of transducer signal at 2 microseconds per word, and with 12 bit voltage resolution. Each accelerometer trace from each impact tool drop was acquired by the scope and stored on floppy disc for later analysis.

2.3 TEST LOCATION

Forty test locations in Brant and Waterloo counties were chosen. These test locations were on six roads varying from low quality surface treatment to a new section of a major divided highway. Two of the roads underwent extensive testing at 50 m intervals through known "fault" sections of the road.

Each test location was measured with the DYNAFLECT trailer, providing an objective comparison base for the impact tool results. The impact tool was dropped twice at each test location, providing a total of 80 tests points and a measure of the repeatability of this response method of pavement measurement. The following descriptions summarize the characteristics of the tested roads.

WAT #49

0+000 to 0+100 - paved with high base
0+150 to 0+350 - paved with high water table base (pond on both sides)
0+400 to 0+650 - paved with base rising above pond level

HPI Driveway - paved on gravel base

Brant #28

0+200 to 0+600 - paved with strong base
0+650 to 1+350 - chip seal with minimal base with dip adjacent to swamp from approximately 1+000 to 1+300

403 - new 9" pavement on deep base

Blue Lake Road - chip seal with minimal base
location #1 adjacent to swamp
location #2 on a hill

2.4 TEST RESULTS

2.4.1 Preliminary Results

Preliminary testing was conducted on the HPI parking lot in order to determine the optimum configuration for further testing. The following configuration was selected.

An 88 pound (40 kg) bar with no bit provided an acceptable response. The bottom radius was 6 inches (15.24 cm). The drop height selection was 40 cm yielding an impact velocity of 2.8 metres per second.

2.4.2 Data Reduction

With 80 traces of 4K words per trace, significant attention was paid to automating the data reduction. This section summarizes the data reduction steps.

2.4.2.1 Nicolet Dump

The data stored on Nicolet Disc was transferred into an IBM PC-XT file system through an RS232 interface.

2.4.2.2 Data Reduction Summary

For each data point, key parameters were:

a) Peak Acceleration - corresponded to the maximum deceleration of the impact bar, or the peak voltage on the data trace

b) Peak Velocity - corresponded to the point of maximum rebound velocity of the impact bar, determined from the peak integrated voltage of the data trace

c) Displacement - corresponded to the maximum deflection point into the pavement and the pavement deflection when the impact bar left contact with the pavement. Displacements were determined from the double integration of voltage over the appropriate time interval

2.4.3 Data Summary

The data summary chart includes acceleration, velocity, displacement, and Dynaflect data for each test point. The charts are included as Tables 2-1 through 2-4.

2.5 ANALYSIS OF RESULTS

The response test results were compared with Dynaflect results. The Dynaflect is a standard pavement structure measurement device, and some degree of correlation was required to verify pavement structure measurement by the response method.

2.5.1 Accelerometer Traces

Figures 2.3 and 2.4 each compare accelerometer voltages between a test point at a sound pavement location to a test point at a nearby weak pavement location. Each figure is from a different road, but both plots demonstrate a similar difference between the strong and weak pavement structures.

2.5.2 General Trends

A study of the summary of results charts showed several trends.

2.5.2.1 Acceleration

Peak Acceleration corresponded with the total structure measures from the Dynaflect.

2.5.2.2 Velocity

Rebound velocity corresponded with the total structure measures of the Dynaflect.

2.5.2.3 Displacement

Neither displacement measure corresponded significantly with Dynaflect results. However, displacements were generally less than 2.5 mm on a paved surface and greater than 2.5 mm on a surface treated surface. This was noticeable during testing, as a surface treated road underwent permanent visible deformation as a result of the impact.

TABLE 2-1 RESPONSE TESTS: DATA SUMMARY

ROAD	CHAINAGE m	PEAK ACCEL. G.s.	REBOUND VELOCITY m/s	MAX. DISPL. mm.	FINAL DISPL. mm.	DYNAFLECT 1 mils.	2 mils.	3 mils.	4 mils.	5 mils.
Waterloo #49	0+000	180.0 183.4	0.236 0.258	2.56 2.88	2.42 2.81	.60	.32	.18	.11	.06
	0+050	172.8 170.2	0.140 0.144	3.09 2.94	3.05 2.88	.68	.42	.28	.21	.17
	0+100	170.2 162.9	0.300 0.216	3.22 2.89	3.11 2.79	.81	.56	.44	.36	.33
	0+150	177.3 173.0	0.098 0.141	2.66 2.78	2.62 2.72	.93	.69	.52	.42	.36
	0+200	151.9 159.0	0.106 0.171	3.48 3.56	3.46 3.52	.80	.50	.34	.23	.18
	0+250	147.4 142.5	0.0 0.0	3.26 3.51	3.26 3.51	.87	.54	.33	.20	.15
	0+300	160.1 170.3	0.274 0.250	3.00 3.50	2.91 2.27	.84	.51	.32	.19	.14
	0+350	191.5 181.4	0.159 0.212	2.71 3.16	2.61 3.10	.86	.60	.44	.33	.27
	0+400	205.0 189.1	0.360 0.260	2.92 2.70	2.80 2.64	.75	.52	.40	.33	.26
	0+450	182.5 215.2	0.179 0.378	2.45 2.29	2.42 2.17	.75	.51	.36	.26	.20
	0+500	Excessive traffic at intersection				.52	.33	.23	.17	.14

TABLE 2-2 RESPONSE TESTS: DATA SUMMARY

ROAD	CHAINAGE m	PEAK ACCEL. G.s.	REBOUND VELOCITY m/s	MAX. DISPL. mm.	FINAL DISPL. mm.	DYNAFLECT 1 mils.	2 mils.	3 mils.	4 mils.	5 mils.
Waterloo #49	0+600	175.3	0.188	2.91	2.84	.56	.32	.19	.11	.06
		192.1	0.210	2.82	2.75					
	0+650	156.1	0.126	3.51	3.49	.63	.32	.18	.11	.05
HPI	Driveway	137.5	0.0	3.41	3.41	See earlier test on page 4				
		130.5	0.0	3.52	3.52					
Brant #28	0+200	247.3	0.460	1.84	1.55	.37	.17	.10	.05	.04
		250.0	0.401	2.34	2.27					
	0+250	239.2	0.389	2.12	1.95	.48	.20	.05	.02	.01
		229.0	0.401	1.95	1.73					
	0+300	245.6	0.472	1.68	1.34	.50	.24	.11	.04	.02
	0+350	264.6	0.402	1.60	1.48	.49	.25	.12	.05	.03
		250.4	0.395	1.84	1.57					
	0+400	237.5	0.345	1.95	1.80	.79	.38	.18	.11	.05
		224.9	0.336	2.11	1.98					
	0+450	254.1	0.436	1.85	1.74	.53	.28	.16	.11	.05
		245.1	0.412	2.10	1.95					
	0+500	266.9	0.493	2.13	2.01	.51	.26	.11	.04	.02
		249.8	0.422	1.94	1.82					
	0+550	239.3	0.475	1.68	1.37	.37	.18	.10	.04	.03
		Computer Error in Integration Calculations								

TABLE 2-3 RESPONSE TESTS: DATA SUMMARY

ROAD	CHAINAGE m	PEAK ACCEL. G.s.	REBOUND VELOCITY m/s	MAX. DISPL. mm.	FINAL DISPL. mm.	DYNAFLECT 1 mils.	2 mils.	3 mils.	4 mils.	5 mils.
Brant #28	0+600	232.4 212.8	0.381 0.362	1.91 2.11	1.68 1.95	.47	.24	.13	.06	.03
	0+650	150.7 148.5	0.058 0.066	3.53 4.10	3.52 4.09	.66	.36	.19	.10	.03
	0+700	138.4 134.1	0.091 0.037	3.20 3.20	3.18 3.20	.66	.30	.13	.04	.03
	0+750	164.3 155.0	0.189 0.159	2.64 3.29	2.56 3.24	.66	.28	.11	.04	.02
	0+800	146.3 164.9	0.023 0.129	3.29 2.99	3.29 2.96	.84	.36	.12	.04	.02
	0+850	153.6 144.5	0.042 0.0	2.96 3.20	2.96 3.20	.81	.38	.16	.05	.03
	0+900	157.3 145.8	0.088 0.089	2.86 3.24	2.84 3.23	.81	.39	.16	.05	.02
	0+950	158.3 148.1	0.0 0.0	3.14 3.33	3.14 3.33	.84	.42	.18	.06	.03
	1+000	138.2 119.9	0.140 0.196	3.16 3.58	3.13 3.52	.66	.34	.17	.09	.03
	1+050	131.5 162.8	0.0 0.217	4.10 3.43	4.10 3.34	2.67	1.74	1.26	.87	.59

TABLE 2-4

RESPONSE TESTS: DATA SUMMARY

ROAD	CHAINAGE m	PEAK ACCEL.. G.s	REBOUND VELOCITY m/s	MAX. DISPL. mm.	FINAL DISPL. mm.	DYNAFLECT 1 mils.	2 mils.	3 mils.	4 mils.	5 mils.
Brant #28	1+100	173.6 146.8	0.231 0.152	2.91 3.24	2.79	.87	.70	.69	.66	.62
	1+150	141.2 157.2	0.0 0.090	3.50 3.24	3.50 3.21	.74	.32	.12	.04	.02
	1+200	137.4 133.2	0.0 0.0	3.81 3.85	3.81 3.85	4.50	3.50	3.20	2.80	2.35
	1+250	169.4 168.9	0.166 0.196	2.65 2.80	2.60 2.72	0.90	.60	.51	.46	.41
	1+300	140.3 138.6	0.0 0.006	3.34 3.44	3.34 3.44	2.90	1.62	.70	.29	.14
	1+350	136.9 131.6	0.098 0.155	3.44 3.72	3.44 3.72	.81	.40	.22	.13	.06
Highway #403	Princeton	211.7 200.7	0.259 0.239	2.26 2.35	2.24 2.28	.54	.35	.23	.17	.13
HPI	Driveway	150.4 155.7	0.0 0.0	2.98 3.10	2.98 3.10	1.47	.80	.29	.16	.10
Blue Lake Road	#1	112.1	0.021	4.63	4.63	2.28	1.61	---	.35	.21
	#2	138.2 163.0	0.131 0.254	3.97 3.62	3.93 3.45	.71	.51	---	.21	.09

2.5.3 Scattergraphs

The Dynaflect Sensor 1 measure refers directly to the load carrying capacity of the structure as a whole at that point. Figures 2.5 and 2.6 are plots of Peak Acceleration versus Sensor 1 and Rebound Velocity versus Sensor 1. Both Response parameters show inverse correlation with the Dynaflect structure measures.

2.5.4 Statistical Comparison of Results

A regression analysis program was used to determine the model and correlation for Response and Dynaflect results.

2.5.4.1 Correlation

The following table summarizes the correlation runs. No multivariable runs were conducted.

Seq.	Y (Response Parameter)	X (Dynaflect Parameter)	Correlation Coefficient
1	Peak Acceleration	1/S1	0.771
2	Peak Acceleration	1/(S1-S5)	0.762
3	Rebound Velocity	1/S1	0.813*
4	Rebound Velocity	1/(S1-S5)	0.823
5	Max. Displacement	1/S1	0.722

An extremely wide variety of roadway conditions were tested. For example, test points included:

- locations with varying degrees of alligator cracking up to severe
- surfaces that were surface treated, tar, paved, and surface treated overlayed with pavement
- substructure conditions from almost non-existent base over swamp to the substructure of a major divided highway
- test locations over culverts
- data that was collected in early spring and late summer

2.5.5 Fault Discrimination

Two roads were tested through a fault section. WATERLOO Road # 49 was tested through an area surrounded by ponds, from chainage 0+150 to 0+350 feet. Figure 2.7 compares the Dynaflect and Response test results through this section. Both methods show lower 'strength' at the pond chainages.

Figure 2.8 compares the Dynaflect and Response test results for Brant Road # 28. On the high quality section of this road, chainages 0+200 to 0+600 feet, the Dynaflect is more sensitive to the structure than the Response method. The fault at chainage 0+400 was not visibly apparent in the pavement or shoulder, and was probably a problem in the base structure. The lower quality base and pavement from chainage 0+650 onwards was apparent from the Response test results. The swamp and culvert sections (1+000 to 1+300) were not differentiated by the Response Peak Deceleration, but were apparent from the Response Rebound Velocity.

2.6 CONCLUSION OF RESPONSE TESTS

a) Dynaflect and Response measurements show good statistical correlation (R = .813) over a wide variety of pavement conditions. Specifically, Peak Acceleration and Rebound Velocity of the probe show sufficient differentiation and repeatability to replace Dynaflect measurement (Sensor 1) on all pavements with Sensor 1 readings of less than one mil.

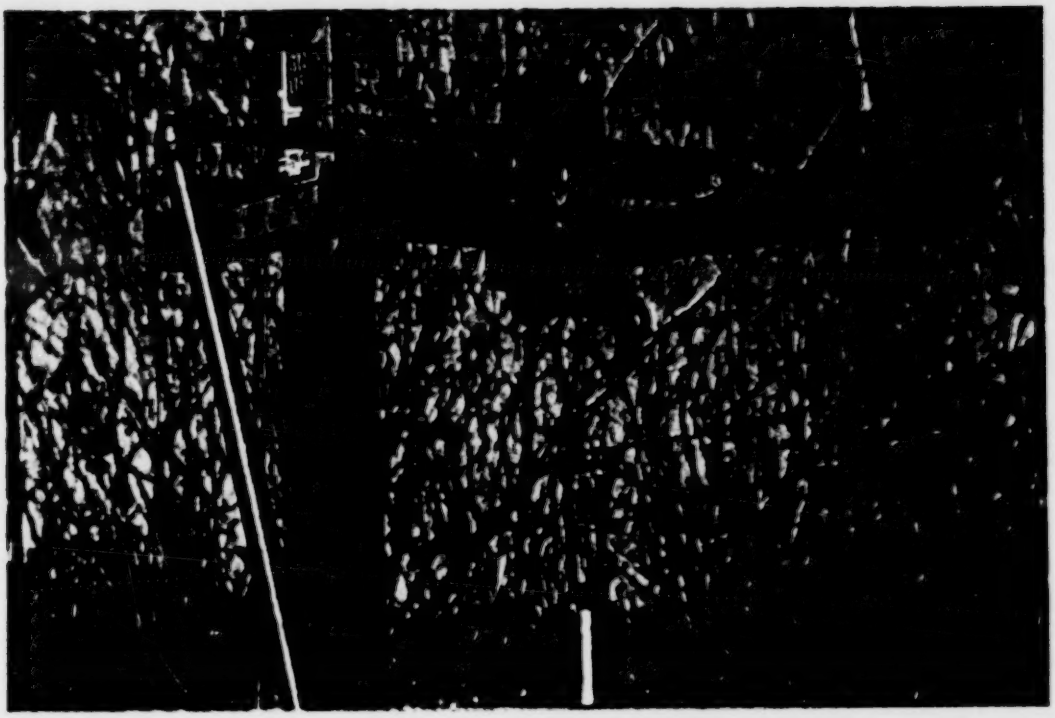
b) Displacement measures provided information on the integrity of the surface layer of the pavement.

c) The Responce method detected faults in pavement sections, although faults that were most likely deep in the base were not differentiated strongly from non-faults.

d) The Response method parameters individually do not fully characterize the structural information in the impact response signal. Some faulting is most apparent in the Peak Acceleration, other faulting is more apparent in the Rebound Velocity parameter.

FIGURE 2.1: IMPACT TOOL

FIGURE 2.2: LIFTING DEVICE



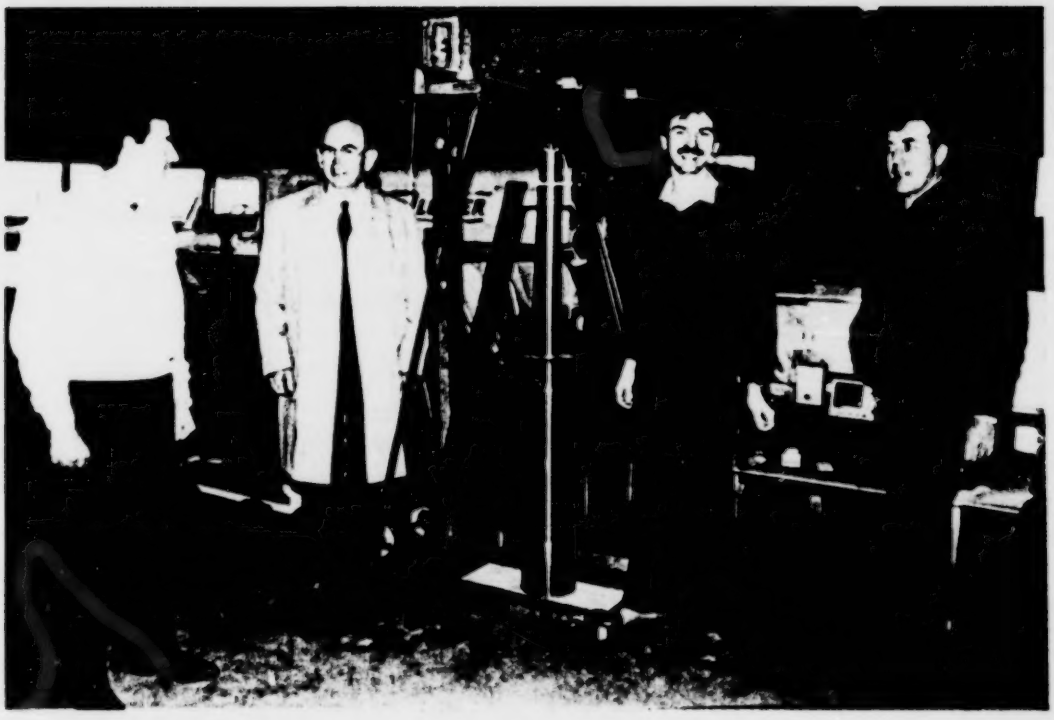


FIGURE 2.3: FILTERED VOLTAGE PLOT

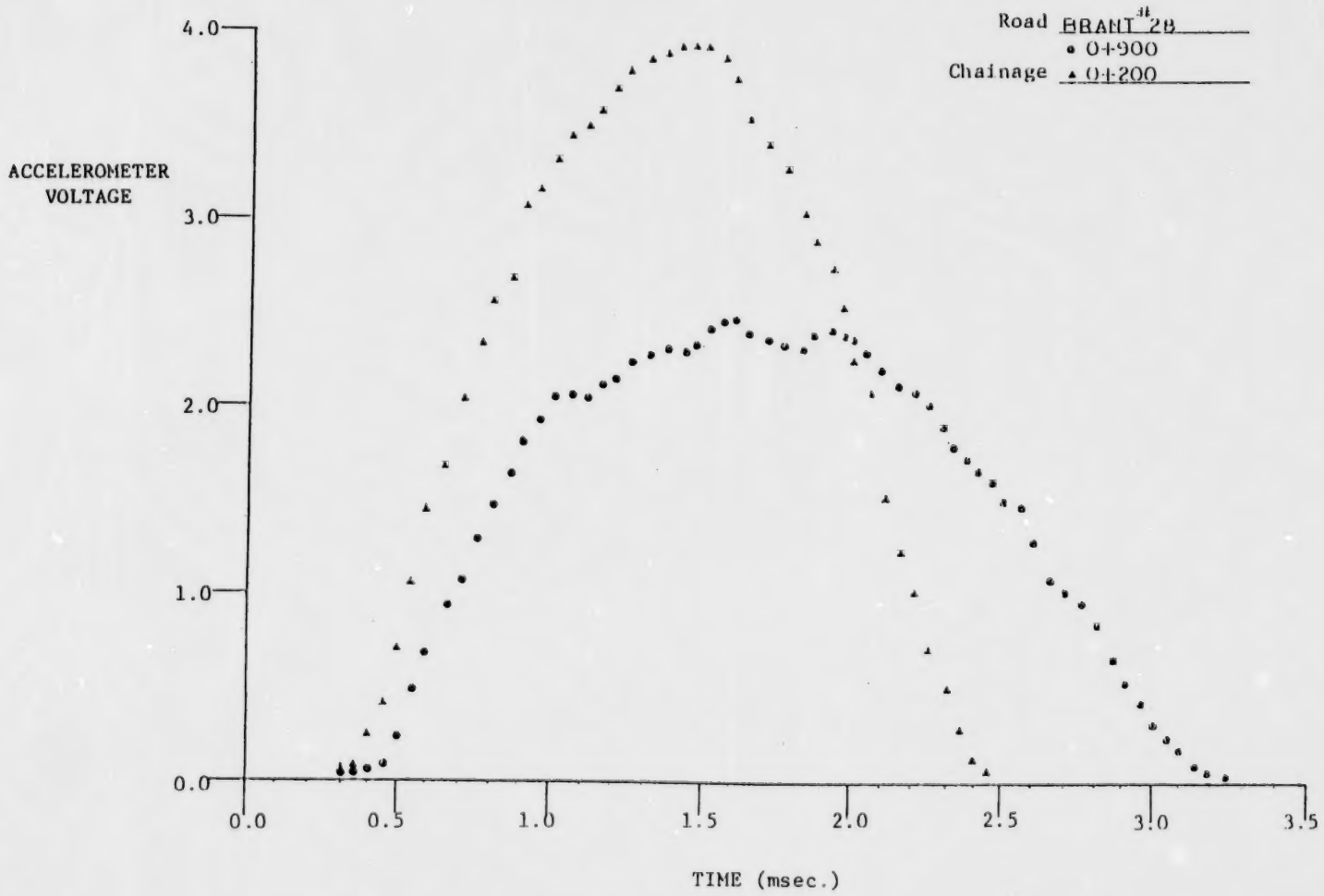


FIGURE 2.4: FILTERED VOLTAGE PLOT

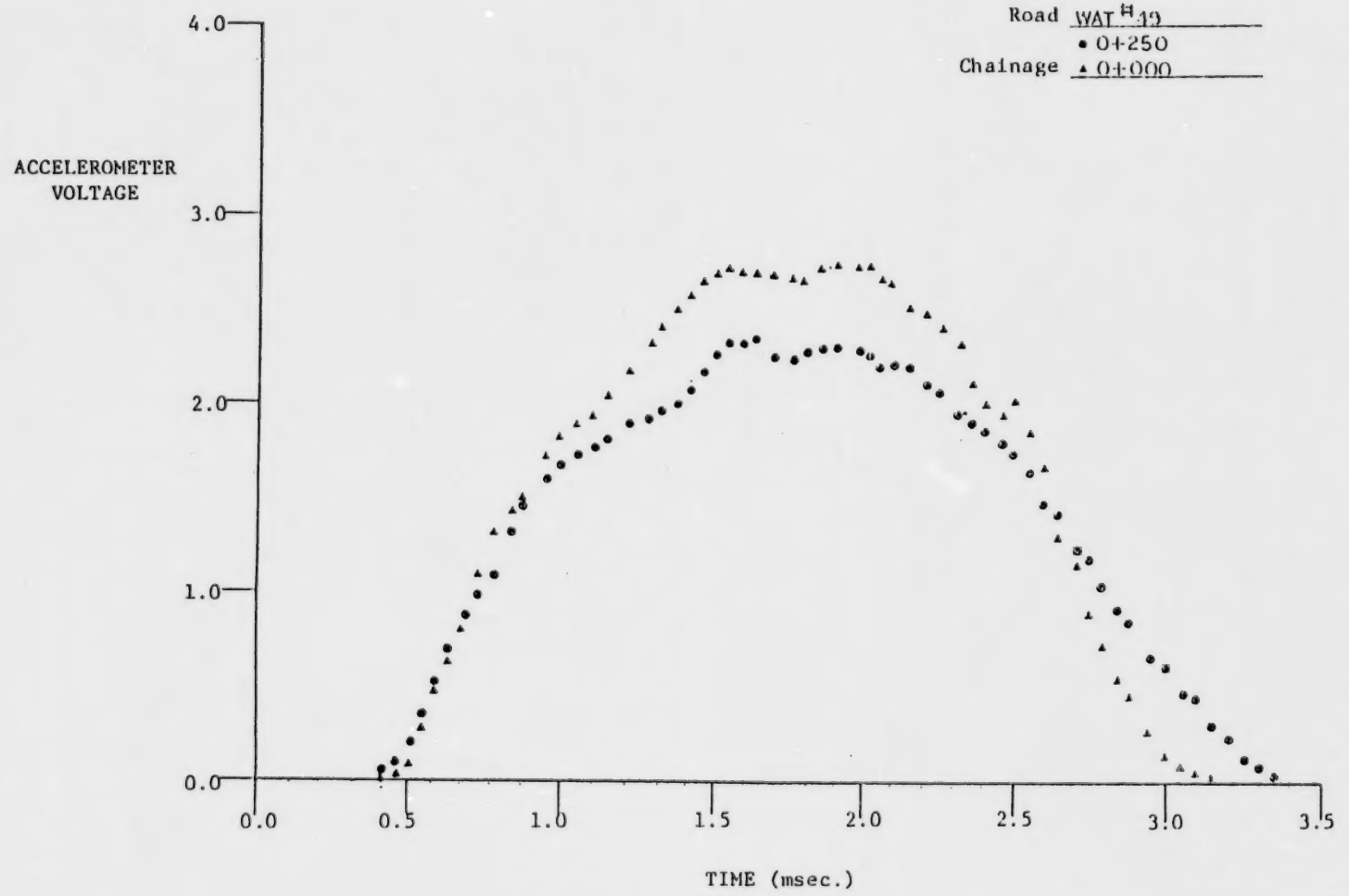


FIGURE 2.5: RESPONSE vs. DYNAFLECT: ACCELERATION

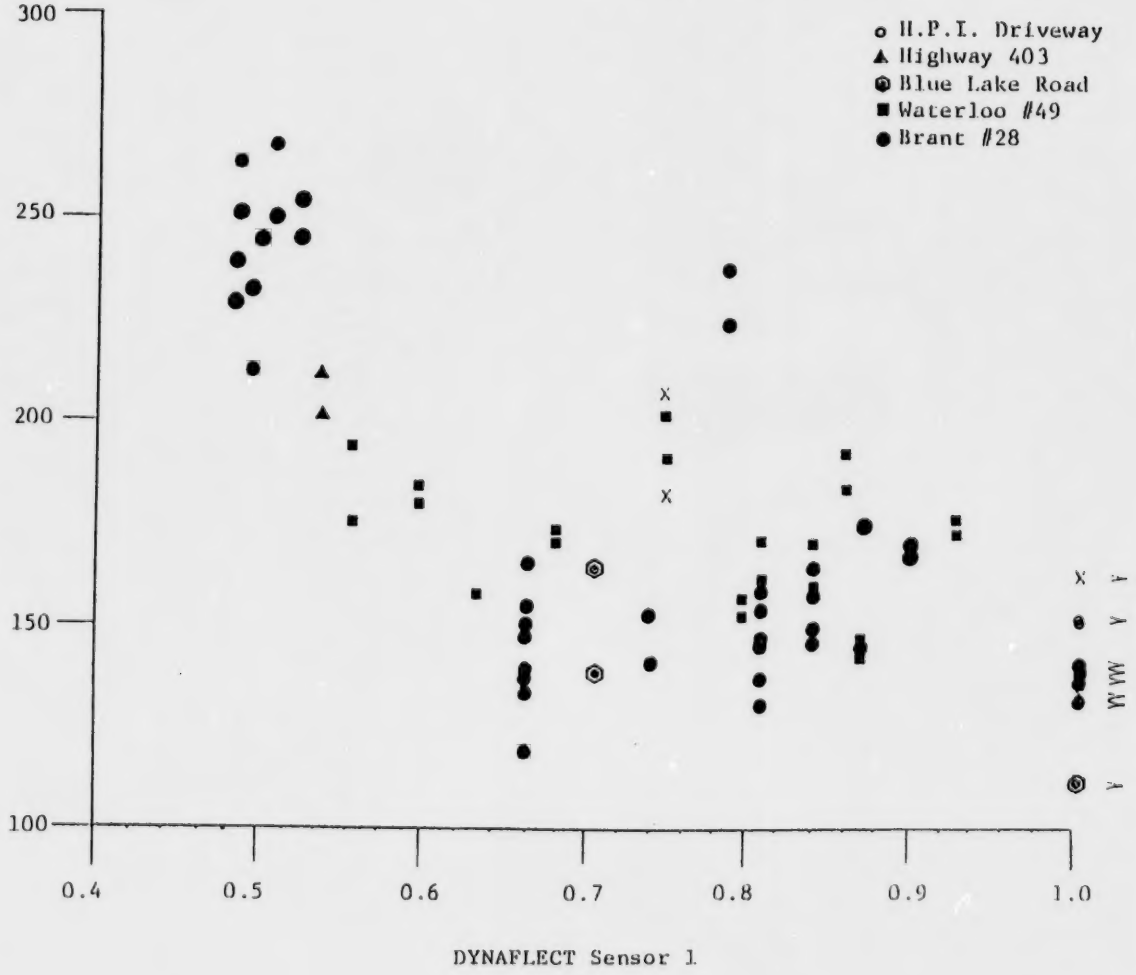


FIGURE 2.6: RESPONSE vs. DYNAFLECT: VELOCITY

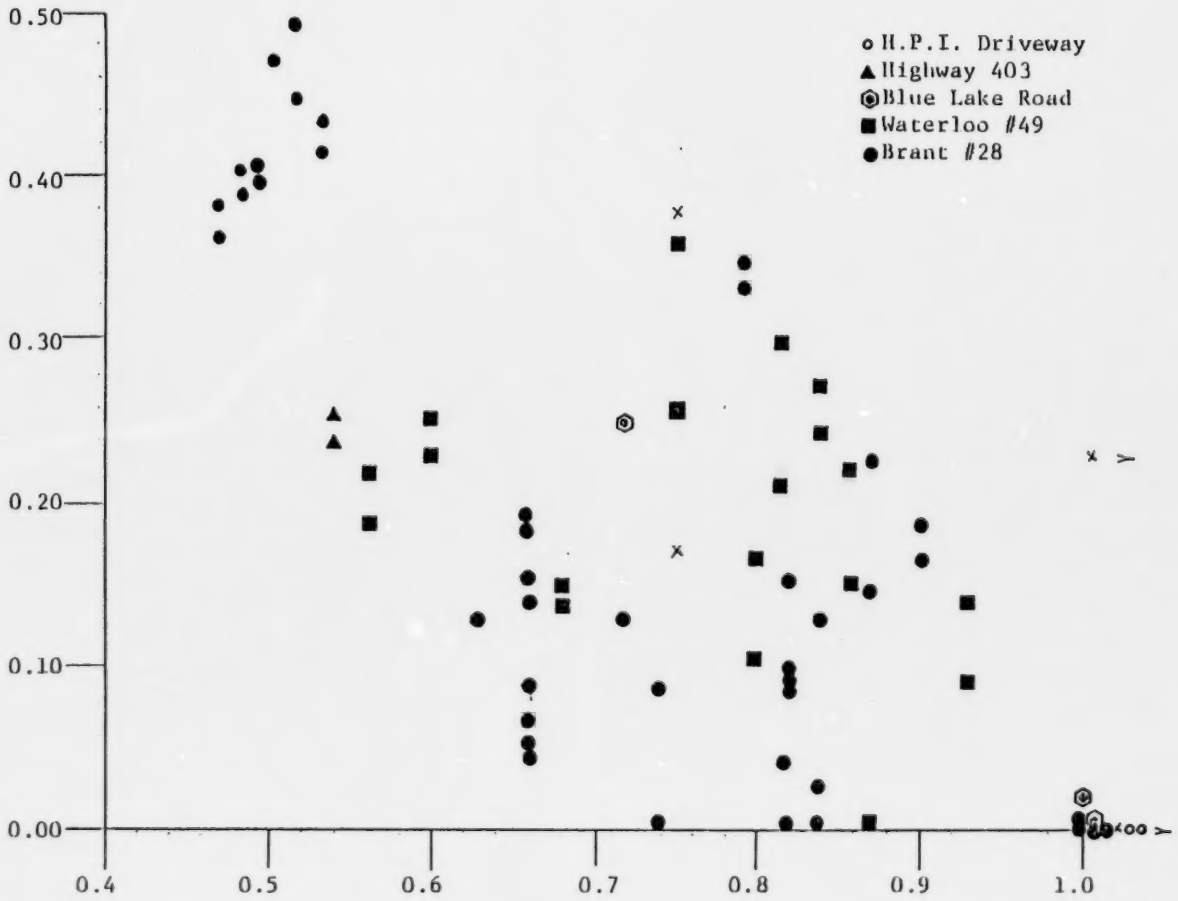


FIGURE 2.7 FAULT DETECTION ON WATERLOO # 49

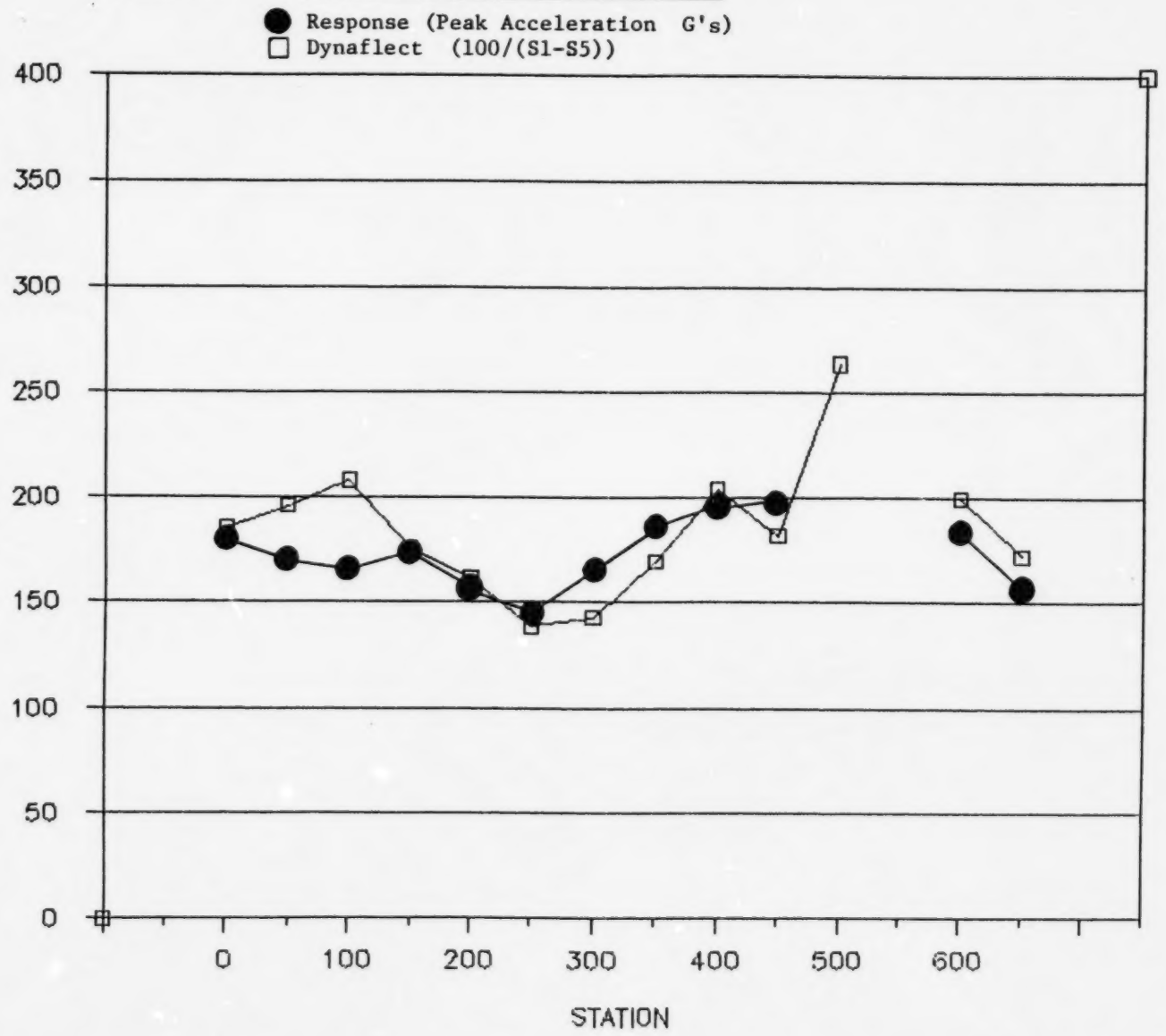
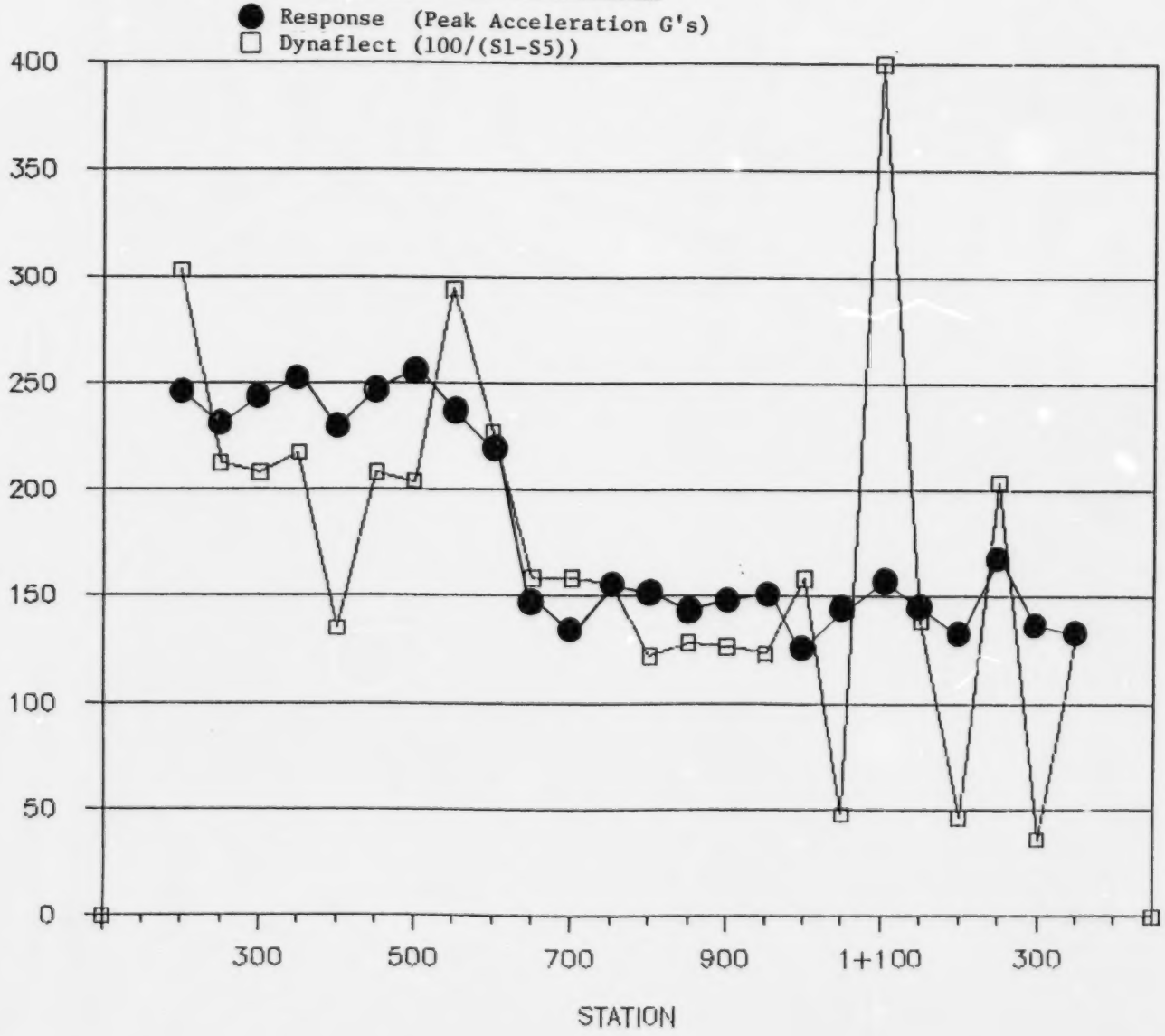


FIGURE 2.8 FAULT DETECTION ON BRANT # 28



3. THEORY OF PAVEMENT RESPONSE

This section outlines the computer models developed to help understand the experimental results and extrapolate design parameter effects.

3.1 THEORY OF IMPULSE TESTING

3.2 MODEL DEVELOPMENT

3.3 DISCUSSION OF MODEL

3.4 REFERENCES

3.1 IMPULSE TEST - THEORY

The basic measurement being made was in all respects equivalent to the Green's function (three dimensional) response of a system to an impulse stimulus. The basic theory of this testing method follows assuming familiarity with the basic Fourier Transform and time/frequency domain response. Initially, given any physically realizable system with a transfer function h(t), an input f(t) and a response g(t), then

$$f(t) \longrightarrow h(t) \longrightarrow g(t)$$

$$g(t) = f(t) * h(t) \quad \text{where } * \text{ denotes convolution}$$

in the Time Domain. Moving into the Frequency Domain using a Fourier transorm pair where:

$$f(t) \Longleftrightarrow F(w)$$
$$h(t) \Longleftrightarrow H(w)$$
$$g(t) \Longleftrightarrow G(w)$$ then the process of

Convolution in the Time Domain reduces to multiplication in the Frequency Domain:

$$G(w) = F(w)\,H(w)$$

Using the Delta Function (an Impulse stimulus) as input in the Time Domain noting that

$$\text{Delta}(t) \Longleftrightarrow 1$$

Then the response to this input is simply:

$$G(w) = H(w)\ 1 = H(w)$$ the response is the

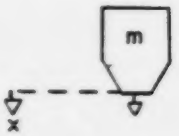
Transfer function itself. With H(w) known, the response to any stimulus can be found. This fact is the basis for Impulse Testing.

3.2 MODEL DEVELOPMENT

There are three distinct regions of time, each of which requires its own model.

3.2.1 Region 1

The first is the period of time before the probe hits the surface of the pavement. The probe mass is under acceleration by either gravity or a physically realizable system such as hydraulics or pneumatics. The probe attains a velocity, Vo, which will be the impact velocity in Region 2.



$$F = ma$$

$x = b$ Pavement Surface

$$A = g$$

$$V = gt$$

$$X = 1/2\ gt^2$$

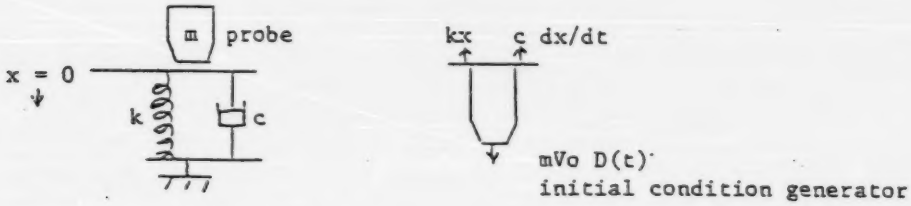
$$Vo = \sqrt{2\ gb}$$

$$E_k = mgb$$

3.2.2 Region 2

The probe contacts the surface of the pavement. The velocity goes to zero, the pavement is deformed, the pavement rebounds, and the probe is pushed back to the starting point attaining a maximum rebound velocity. Frictional losses in this period are accounted for by using a Kelvin Viscoelastic model.

The probe/pavement/subgrade is treated as an integral system and gravitational acceleration is negligible with respect to the other forces acting.



$$m\,d^2x/dt^2 + c\,dx/dt + kx - mVo\,D(t) = 0$$

going to Laplace Notation

$$m\,s^2\,X(s) + c\,s\,X(s) + k\,X(s) - mVo = 0$$

$$X(s) = \frac{Vo}{s^2 + \frac{c}{m}s + k/m}$$

Classic form

$$X(s) = Vo\,\frac{Wn^2}{s^2 + 2ZWn\,s + Wn^2}$$

$$Wn = \sqrt{k/m} \qquad Z = \frac{c}{2\sqrt{km}}$$

This, of course, leads to the underdamped, overdamped and critically damped solutions in the time domain.

Underdamped Solution

$$X(t) = \frac{VoWn}{\sqrt{1-Z^2}} \; e^{-ZWnt} \sin\left(\sqrt{1-Z^2}\; Wnt\right)$$

plots shown are normalized displacement

$$\frac{X(t)}{Wn\ Vo} \quad \underline{vs} \quad Wnt$$

for Z selected.

$$V(t) = \frac{Vo\ Wn^2}{\sqrt{1-Z^2}} \; e^{-ZWnt}\left[\sqrt{1-Z^2}\cos\left(Wnt\sqrt{1-Z^2}\right) - Z\sin\left(Wn\sqrt{1-Z^2}\ t\right)\right]$$

plots are $\frac{V(t)}{Vo\ Wn^2}$ $\underline{vs}$ Wnt

$$a(t) = \frac{Vo\ Wn^3}{\sqrt{1-Z^2}} \; e^{-ZWnt}\left[(2Z^2-1)\sin\left(Wn\sqrt{1-Z^2}\ t\right) - 2Z\sqrt{1-Z^2}\cos Wn\sqrt{1-Z^2}\ t\right]$$

plots are $\frac{A(t)}{Wn^3\ Vo}$ $\underline{vs}$ Wnt

Note that sanity checks when Z=0,

$$X(t) = Vo\ Wn \sin Wnt$$
$$V(t) = Vo\ Wn^2 \cos Wnt$$
$$U(t) = -Vo\ Wn^3 \sin Wnt$$

This is the perfectly elastic case with no friction losses.

3.2.3 Region 3

This period of time begins when the probe leaves the pavement. The energy delivered to the pavement has been returned to the probe less frictional or plastic losses. The probe has a rebound velocity and the time to zero velocity is controlled by gravitational acceleration. This region is of minimal interest since no pavement/subgrade information is available.

3.2.4 Definition of Formula Notation

F = Force

A,a = Acceleration

X,x = Displacement from reference zero

V,v = Velocity

t = elapsed time

D(t) = Dirac Delta Function

s = Laplace Operator

m = Mass

k = Elastic Force Constant

c = Frictional Force Constant

Vo = Impact Velocity of Probe

Wn = System natural resonant frequency in radias per second

Z = Constant Gravitatioal Acceleration

E_K = Kinetic Energy

When used to denote a function, capital letters apply to the Laplace or Frequency Domain, small letters apply to the Time Domain.

3.3 DISCUSSION OF MODEL FOR REGION 2

Region 2 is the most interesting period of time. A computer simulation was run to gain insight into the physics of the system. Some results are shown in this section.

When the damping constant Z is set to zero, the purely elastic case yields an oscillatory output. Here the energy in the probe is 100% converted into elastic deformation. This is a boundry maximum.

$$X \text{ max.} = \sqrt{2\ mgb/k}$$

In the case of any Z to find the point of maximum deflection, the first derivative is set to zero and yields

$$t = \tan^{-1} \left(\sqrt{1-Z^2}\ /Z\right)$$

$$Wn = \sqrt{k/m}$$

As reported in the experimental results, the time to maximum response varied as the square root of the mass.

The contact area will vary the effective k of the system, with k varying directly with the contact surface area. In order to maintain the response time required, if the surface contact area is increased, the mass must be increased by the same factor.

When the mass was increased from 125 to 225 pounds (56.7 to 102 kg), the time increased by one third. The model used would indicate a change of 225/125 or 34 percent. The change in contact areas by the increase in radius from 24 inches (61 cm) to 6 inches (15.24 cm) would be predicted to change the time by the square root of the ratio of areas or by a factor of four. If it is required that response time be increased further, either the mass must be increased or the contact area of the probe decreased.

The longer the response time, the greater the depth of investigation. Compressive waves travel in earth materials at a rate of between 131 us/m to 656 us/m for pure water. Pavement composites ranging from 10% void to 40% void and crushed stone to clays will yield travel times of 183 to 459 us/m. A 3 millisecond response would represent a peak response at 1.5 millisecond coming from a maximum depth of from 4 to 1.6 m.

Some of the empirical data show zero or apparently slightly negative rebound velocity measurements. These would be from materials having low coefficients of elasticity. This velocity may be increased by increasing the impact velocity.

Figure 3.1 shows the normalized displacement (f(t)) versus resonant frequency (Wnt) with damping coefficient (ζ) as a variable.

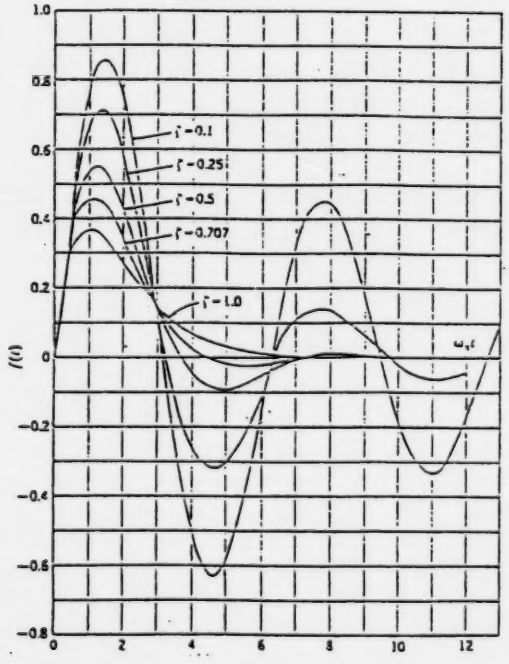


Figure 3.1 REGION 2 DAMPING EFFECTS

3.4 REFERENCES

1) **Nordal, R.S.,** "The Bearing Capacity a Chronic Problem in Pavement Engineering", Proceedings Vol. 1, Bearing Capacity of Roads and Airfields, The Norwegian Institute of Technology, Trondheim June 1982, Tapir N-7034 Trondheim-NTH.

2) **Majidzadeh, Kamran,** "An Overview of Deflection Parameters for performance analysis", same source as (1).

3) **D'Azzo, J.J. and Houpis, C.H.,** "Feedback Control System Analysis and Synthesis", McGraw-Hill Book Co., New York 1960.

4) **Sears, Francis Weston and Zemansky, Mark W.,** "College Physics", Addison-Wesley Pubishing Company Inc., Reading, Massachusetts, 1960.

4. CONCEPTS FOR IMPLEMENTATION

This section summarizes high speed implementation possibilities for the response method.

4.1 INTRODUCTION

4.2 CONCEPTS

4.2.1 WHEEL DROP

4.2.2 POGO STICK

4.2.3 AXLE MOUNTED IMPACT GUN

4.2.4 FIXED IMPACT GUN

4.1 INTRODUCTION

In considering different implementations for the methodology of the static experiment in a dynamic test system, several common criteria.

Any devices used for dynamic testing must satisfy the following conditions:

a) Decelerate to zero velocity from the vehicle forward speed with respect to the pavement.

b) Match the pavement surface with allowance for pavement irregularities.

c) Load and unload the pavement with a consistent force of sufficient magnitude to elicit response from the pavement and subgrade.

d) Remain in place within bounds to ensure that the response to the above stimulus is measured.

e) Retract the measuring device.

f) Accelerate to vehicle speed.

The following four concepts satisfy these conditions in varying ways.

4.2 CONCEPTS

The following descriptions outline conceptual implementation of a Dynamic Tester using the experimental methodology.

4.2.1 Wheel Drop Measurements

4.2.1.1 Measurement

In the simplest form the wheel is released and drops to the pavement surface to make a measurement. The multiple sensors allow resolution of direction and mangitude of the resulting response. The velocity of the wheel edge with respect to the pavement surface is zero. In a more complex realization a wheel with lower mass is accelerated toward the pavement by hydraulic or pneumatic means. The wheel is then retracted, raised and stands ready for the next measurement.

4.2.1.3 Advantages

Ease of probe recovery. Probe is automatically decelerated to zero velocity with respect to pavement surface. Simplicity of concept.

4.2.1.4 Disadvantages

Gyroscopic action on turns. Heavy weight spinning at high speeds. Uncertainty of measurement validity under these circumsances. Difficulty of varying probe contact surface area during prototype testing. Complexity of multiple rotating sensors.

4.2.2 Swinging Pogo Stick

4.2.2.1 Concept

A telescoping rod which is attached to the vehicle by a hinge is allowed to swing down against the pavement surface and be compressed as the vehicle moves past the point of contact. As the vehicle drives over this point the bottom end of the rod which was in contact swings back and up to the vehicle in the process leaving the pavement.

4.2.2.2 Measurement

The hinged rod is accelerated in the negative direction so that the bottom tip which will contact the pavement will have zero velocity with respect to this surface. After contact the rod is compressed as the vehicle moves forward. The relative position of the vehicle to the point of contact is noted and at the appropriate time an impulse is applied through the solid bottom piece of the rod to the pavement. An accelerometer mounted on the foot of the rod measures the response to this stimulus.

4.2.2.3 Advantages

Slowest rotation due to large equivalent diameter. Remains relatively fixed for duration of measurement.

4.2.2.4 Disadvantages

Complexity of realization.

4.2.3 Axle Mounted Impact Gun

4.2.3.1 Concept

A counter balanced mineral impact gun is radially mounted on a moving axle. This assembly may be best mounted on a towed trailer since a large diameter tire is desirable to reduce the rotational speed of the gun. An impactor with a 0.15 m stroke that is nitrogen spring activated and hydraulically controlled may be used. An accelerometer is mounted on the impactor.

4.2.3.2 Measurement

The position of the gun is tracked relative to the pavement surface. As it rotates so that the impactor is facing the pavement, the gun is fired. The accelerometer output provides the data of the measurement.

4.2.3.3 Advantages

Natural synchronization with the pavement surface. Fast cycle time.

4.2.3.4 Disadvantages

Complexity of the rotating hydraulic/pneumatic system.
Complexity of electrical connection to rotating gun.

4.2.4 Fixed Mineral Impact Gun

4.2.4.1 Concept

A mineral impact gun is mounted in the vehicle with a horizontally resilient shock system is such a way that the impactor will hit the pavement when the gun is fired. The resilience will allow the probe movement as it decelerates and accelerates with respect to the vehicle. The impactor has an accelerometer mounted on it to make the measurement.

4.2.4.2 Measurement

The gun is fired and the impactor hits the pavement surface. Since it was moving forward at the same velocity as the vehicle, this force is vectored (i.e., not perpendicular to the surface). The gun is decelerating as the measurement is made, the shock mount allowing this action. After the measurement, the probe retracts and accelerates to vehicle speed.

4.2.4.3 Advantages

The impact gun is available - no special design. Measurement may be made statically and compared to existing static data. Fast recycle time.

4.2.4.4 Disadvantages

Sudden deceleration after impact. Overall size may be excessive with a large mass probe as required for a long impact time.

5. EQUIPMENT SPECIFICATIONS

This section describes the preliminary specifications that High Speed Deflection Equipment should meet.

5.1 PURPOSE OF EQUIPMENT

5.2 PAVEMENT TYPES

5.3 PAVEMENT TEST LOADING

5.4 OPERATING SPEED

5.5 OPERATING LIFE

5.6 ENVIRONMENTAL

5.7 ACCURACY, REPEATABILITY, RESOLUTION

5.8 OTHER CONSIDERATIONS

5.1 PURPOSE OF THE EQUIPMENT

5.1.1 The purpose of the equipment is to collect measured data indicating the deflection response and associate deflection of flexible pavements under the impulse stimulus applied by an accelerated mass. This measurement is to be made from a vehicle moving forward at a velocity of approximately 60 km/h.

5.1.2 This equipment will increase the speed and safety of measurements of this type compared to existing deflection measuring methods, which all require the measurement to be made from a vehicle which is stopped or moving at creep speed in the traffic lane.

5.1.3 It is expected that data collected by this equipment will be suitable for replacement of data collected by existing Benkelman Beam or Dynaflect devices. Direct replacement is not a necessity since statistically acceptable correlations may form the basis for data substitution.

5.1.4 It is expected that this equipment will make all of the necessary measurements in a single pass over the pavement surface.

5.2 PAVEMENT TYPES

5.2.1 This equipment is intended to indirectly determine the deflection values of flexible pavements over a granular or compacted gravel base.

5.2.2 This equipment shall make measurements with uniform results on roads with asphaltic concrete surface - i.e., flexible pavements or on roadways with asphalt bound surfaces such as surfaces treatments or oil treatments.

5.3 PAVEMENT TEST LOADING

5.3.1 The force applied by the equipment shall be sufficient to provide elastic deformations similar to Dynaflect measurement. Minimal damage shall be inflicted upon the measured surface by this measurement.

5.3.2 Exact probe contact surface and loading shall be provided under the constraints of 5.3.1 to be determined by further testing.

5.3.3 Depth of surface penetration shall be monitored and recorded as a data validation parameter and as a measurement.

5.3.4 The device shall be constructed such that the response will include data from subsurface material to a minimal of at least 1.5 metres in depth.

5.4 OPERATING SPEED

5.4.1 The equipment shall be capable of making valid measurements whilst traveling at a velocity not to exceed 60 km/h.

5.4.2 The measurement must be independant of speed below the maximum velocity or data must be provided to allow validation of measurements taken at other speeds.

5.4.3 The above maximum velocity is equivalent to 16.67 m/s yielding a sample interval of 167.7 m if a ten second cycle time is realized.

5.5 OPERATING LIFE

5.5.1 It is expected that the equipment will be suitable for twenty thousand kilometres of measurement before replacement. The contact probe is expected to be suitable for 10,000 cycles.

5.5.2 The equipment shall be designed and built for maximum serviceability under the field conditions encountered. Sufficient means shall be provided to ensure data validity through field calibration and built in operational checks.

5.6 ENVIRONMENTAL

5.6.1 The instrumentation shall be capable of operation in a range of 0° to 50° C. The probe shall allow an operating range of -20° to 70° C.

5.6.2 The range of relative humidity for operation shall be from 5% to 90% noncondensing for the instrumentation and 0% to 100% with capability of withstanding water spray for the probe.

5.6.3 The equipment shall be capable of storage temperatures in a range from -55° to 100° C.

5.7 ACCURACY, REPEATABILITY, RESOLUTION

5.7.1 The Dynaflect has a measurement range of 0.01 mils to 9.99 mils. An encoder with 10 bits has 1024 discrete quantized outputs and would certainly have the resolution required. Because of availability, a 12 bit encoder would probably be the economical choice. This encoder would have a resolution of one part in 4096.

5.7.2 The accuracy of the mesurement depends upon the knowledge of the transducer conversion accuracy. It is thought that 10% would be acceptable.

5.7.3 Repeatability should depend upon the stability of the electronics package. Over the environmental conditions specified, 5% would be attainable.

5.8 OTHER CONSIDERATIONS

A number of other final specifications will need to be determined during prototype testing.

5.8.1 Safety equipment on vehicle

5.8.2 Axle loads

5.8.3 Surface defect/texture tolerance

5.8.4 Measurement on curves

5.8.5 Desired on-board processing and output format

5.8.6 Correlation of measurement with other devices' measurements

5.8.7 Optimum operating procedures

5.8.8 Diagnostic requirements

6. RECOMMENDATIONS

This section outlines a recommended program for development of the response method into proven high speed deflection capability.

6.1 INTRODUCTION

6.2 THEORETICAL STUDIES

6.3 PROTOTYPE DYNAMIC DEVICE

6.4 TEST PROGRAM

6.1 INTRODUCTION

Several more development stages are required to produce and prove a prototype high speed deflection device based on the response method. The more demanding physical constraints of the dynamic device will require a more comprehensive theoretical model to analyze the expected behaviour of alternative design schemes. Selection and design of the prototype will require effort in dynamics and machine design and possibly hydraulics and pneumatics. In parallel, system processing electronics and software must be developed, enabling final validation testing of the total system.

6.2 THEORETICAL STUDIES

The model presented served to provide guidance during the static tool development. It is recommended that additional studies be undertaken to refine the model and apply it to the question of Dynaflect correlation. Additional parameters besides Peak Acceleration, Rebound Velocity, and Displacement may be identified which will increase the usefulness of the data available when the prototype is built. Elastic moduli and stress/strain relations of pavement and earth materials should be incorporated into the models.

In conjunction with these studies, additional data processing runs should be applied to the data from the prototype in keeping with the above goals. This study will allow the dynamic tool response to be maximized for the parameters selected.

6.3 FABRICATION

A prototype high speed dynamic test machine should be fabricated to meet preliminary specifications and provide a test vehicle for some of the theoretical studies which will lead to a commercially viable machine. In keeping with the development, this prototype should be built, tested and modified as needed to meet this goal.

6.4 TEST PROGRAM

Tests will first be run on the test roads used during Phase 1 to see that dynamic device measures the appropriate parameters. Additional modification and testing will increase the confidence level in the measurements. At this point extensive testing will serve to corroborate the validity of the machine over a variety of Canadian roadways. Software will be developed to provide a maximally useful format in the presented results. It will be a sub-task goal to relate these measurements to pavement and sub-grade mechanical properties.

Figure 6.1 outlines a schedule for this program.

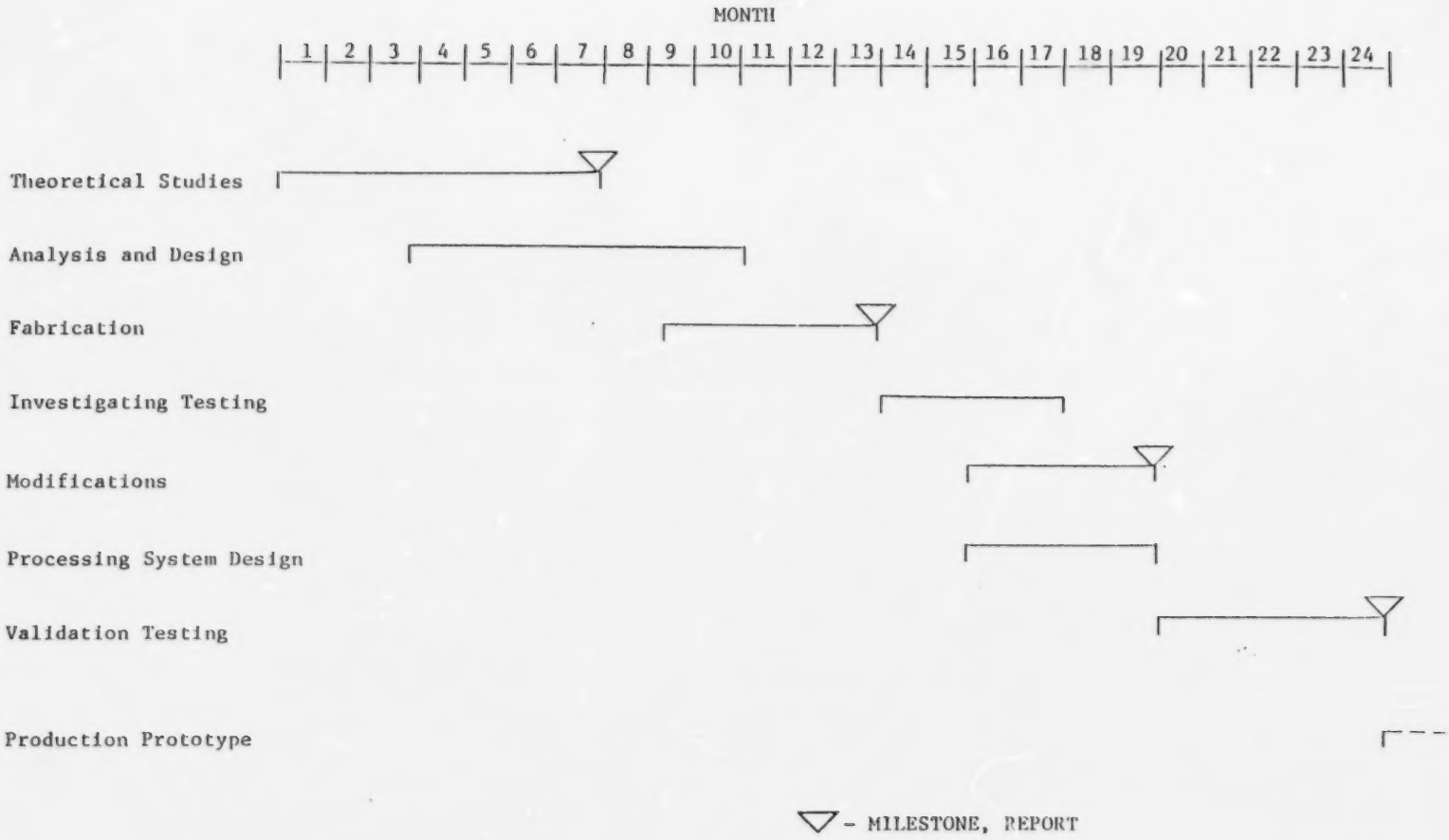

MONTH
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Theoretical Studies
Analysis and Design
Fabrication
Investigating Testing
Modifications
Processing System Design
Validation Testing
Production Prototype
- MILESTONE, REPORT

FIGURE 6.1: SCHEDULE

APPENDIX A. TECHNOLOGY ASSESSMENT

An interim report was submitted during this study. It outlines a recommended change in direction from the original terms of reference. This change in direction was accepted by all agencies involved in funding this project.

A.1 INTRODUCTION
A.2 TECHNOLOGY ASSESSMENT
A.3 RECOMMENDATIONS

A.1 INTRODUCTION

The purpose of this brief interim report is to advise of difficulties with the technology assessment task and make recommendations for an alteration in the approach designed to circumvent them.

The present detailed statement of work centres attention on adaptation of the G.M. profilometer wheel with inclinometers in a setup designed to measure deflection under load as a function of slope. As an alternate to the G.M. wheel setup, optical sensors are proposed. Both methods can be considered to be direct measuring; one being contact and the other non-contact. Both methods try to measure actual deflection in terms of displacement of the pavement by an amount between 2 mils and 75 mils.

The difficulty lies in trying to measure such a minute displacement in the presence of surface micro-roughness and various vehicle motions which create a very unsatisfactory signal to noise ratio.

The desire to have the vehicle travel at 60 km per hour exacerbates the problems due to increased motion and less stability of any candidate reference plane to which the measurements are referred.

A wide range of alternate approaches has been considered without success including the application to the road surface of special spray coatings, mechanical amplifiers, ultrasonic sensors special video distortion measuring systems, etc.

We despair of trying to make direct measurements in this application. We have therefore recommended an alternate approach whereby the deflection measurement is inferred from the pavements' response to a stimulus. This method is not as limited by the same signal to noise ratio. The surface

roughness and vehicle motion do not relate directly to the measurement in terms of displacement as they do in the contact or optical methods.

To date, it has been assumed that the concepts described in the feasibility study were sufficiently viable to permit the detailed design of a demonstration vehicle. A more cautious approach is now advised to conserve funds while the selected concept is proven viable in a fundamental demonstration.

A.2 TECHNOLOGY ASSESSMENT

General

There are two basic problems to be overcome in applying the technology recommended in the feasibility study. 1) The surface micro-roughness of the road often exceeds the deflection by 2:1 to 100:1. 2) the vehicle is travelling at 60 km per hour over a very irregular surface making development of a stable reference plan very difficult.

The deflection measurement under static conditions is relatively minute. (2 - 75 mils). When the vehicle is in motion the magnitude decreases by approximately 1/3 due to the pavement response time.(1)

Inclinometers

The use of inclinometers is key to application of the G.M. wheel to the problem. Inclinometers sense earths acceleration due to earths gravity so that full scale deflection measures 1 g. As the inclinometer travels over the surface attached to a frame supporting the G.M. profilometer wheels for before and after measurement of slope, it experiences accelerations from sources other than earths gravity. The micro-roughness of the surface, the

(1) "Evaluation of the Effects of Axle Loads on Pavements from In Situ Strain and Deflection Measuarements", Alberta Research Council, June 1978.

macro-roughness of the surface and the 3 axes of vehicle motion often produce greater than full scale deflection of the inclinometer output.

In this context acceleration is

$a = d \ w^2$

where a = acceleration in g's

d = displacement in metres (peak)

w = 2TT x frequency in H_z

thus, for a simple example, imagine a sinusoidal surface roughness with wavelength of 1 metre and peak to peak amplitude of 2 mm. Traversing it at 60 km per hour would produce a frequency of

$$f = (1 / 1) \quad / \ (6 \times 10^4 / 3600)$$

$$= 16.66 \ H_z$$

this frequency with a granular size of 5 mm producing an amplitude of say 2 mm would produce an acceleration of

$$a = .001 \times (2TT \times 16.66)^2 = 10.87 \ m / sec^2 \approx 1 \ g$$

It is apparent from this simple example that acceration sensitive slope meters such as pendulums, force balance accelerometers, etc. will have difficulty measuring slope in terms of fractions of 1 g in the presence of extraneous accelerations such as 1 g in the above example.

Optical Sensors

Since the concept of measuring deflection before and during the application of a heavy load demands the comparison of two measurements a stable reference plan is needed. The accuracy of the reference plane must be considerably (at least 5 times) better than the most sensitive measurement required. Attempts to identify technology to create a reference plane stable

to much less than 2 mils have not been successful. The same problems resulting from vehicle motion arise here where unwanted accelerations and even twisting of the vehicle frame add up to an unacceptable signal to noise ratio.

A.3 RECOMMENDATIONS

Our recommendation is that means of making direct measurement of deflection be avoided due to the attendant signal to noise problems. We wish to recommend that an indirect or response type measurement be made where a characteristic response of various pavement types and conditions enables discimination against noise.

For example, assume the equipment setup shown in Figure A-1 where a heavy (150 kg) steel flywheel with suitable non-compressible, frictional coating is mounted on a lifting frame and towed behind a pickup truck. An accelerometer is mounted on the axle of the wheel. The lifting frame allows the wheel to be lifted free of the pavement and dropped under operator control.

Operation

The wheel would be dragged behind the vehicle in contact with the road until it was rotating at vehicle speed. Once lifted the wheel would tend to maintain the same speed momentarily. At prescribed intervals the wheel would be dropped on the pavement surface and the response of the pavement to the wheel would be indicated by the accelerometer and immediately processed by an on-board computer. The anticipated ideal response of the accelerometer is shown in Figure A-2. Of course this signal would contain much noise due to extraneous accelerations but the prospects for removing the noise are much better due to the characteristic response and the opportunity for time domain analysis of the signal. This is the key point in the recommendation.

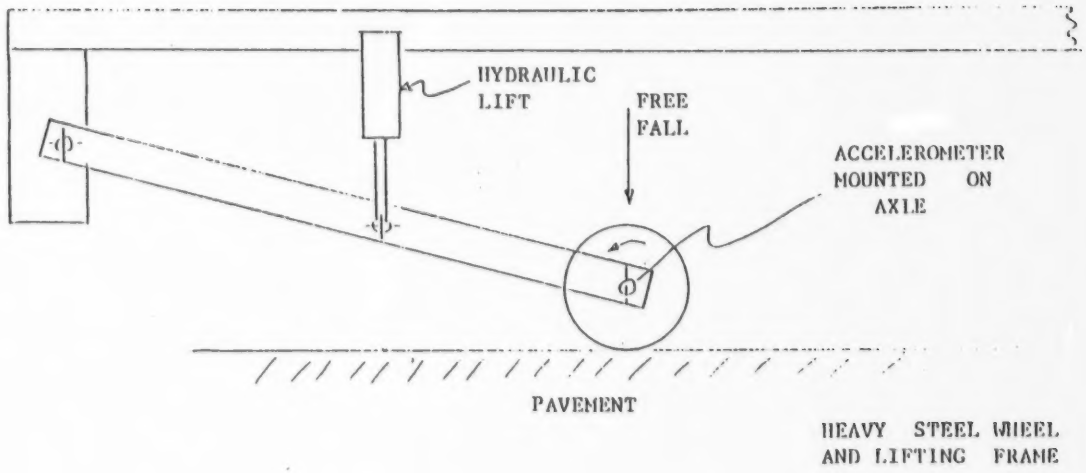


FIGURE A-1 RESPONSE WHEEL

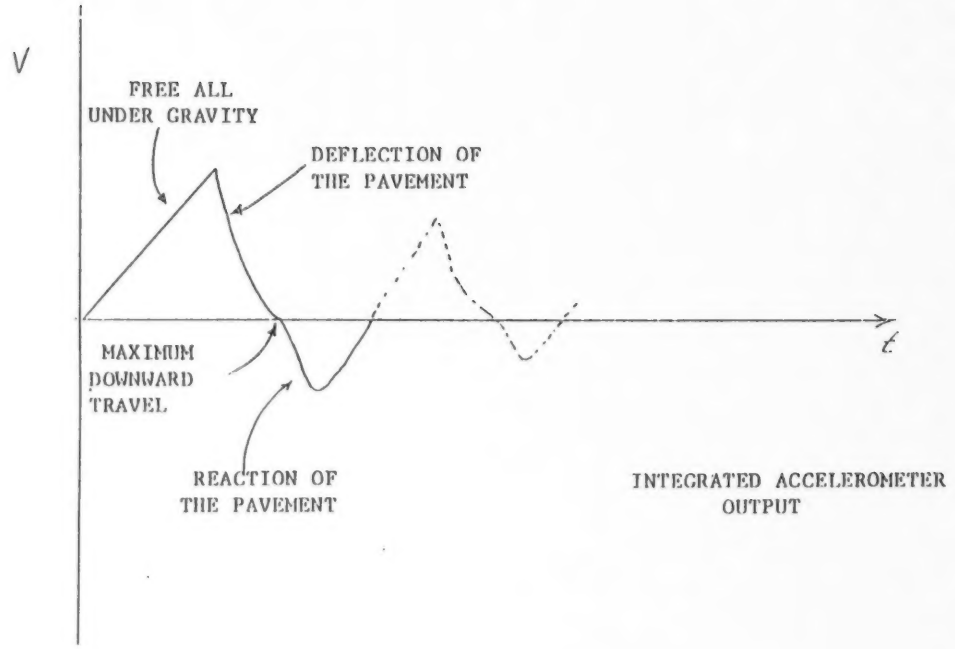


FIGURE A-2 ACCELEROMETER SIGNAL

Anticipated Benefits

- no special heavy weight vehicle required
- more opportunity to capitalize on computer processing of the predictable signal
- very low cost in the ultimate device
- better safety in traffic due to conventional vehicle design
- opportunity to implement the pilot vehicle in stages such as static tests and subsequent dynamic tests
- probably a much lower prototype cost
- a more empirical approach with a good scientific basis